

## Heat transfer and efficiency of dual channel PVT air collector: a review

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### ABSTRACT

Solar energy is free, renewable and environment friendly and has been widely used in electricity generation and thermal energy through photovoltaic thermal (PVT) system. A PVT collector is a combination of a PV panel and a thermal collector in a single unit to simultaneously generate electricity and thermal energy. In this review, mathematical models for dual channel PVT air collectors is presented. This review presents various research and development, as well as heat transfer and thermal modelling of dual channel PVT air collectors. Moreover, various mathematical models that evaluate the performances base on energy and exergy analysis of dual channel PVT air collectors are presented. Energy balance is the basic concept in developing the mathematical models. Generally, steady-state one-dimensional linear first-order differential equations were reported for solution of mathematical model. Energy and exergy efficiencies of dual channel PVT air collectors were 22.5%-67% and 3.9%-58%, respectively.

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## 1. INTRODUCTION

Currently, fossil fuels are scarce and expensive, and its future cost and availability are uncertain. Hence, the usage of solar energy in drying of agricultural products will probably increase and further become economically feasible in the near future. Solar energy is a major renewable energy source that has the potential to supply daily energy consumption without polluting the environment. Solar radiation can be converted into electrical and thermal energies by using a photovoltaic (PV) panel and solar collector. The concept of combining a PV with solar thermal collector to obtain electrical and heat energy is not new but has gained limited research attention. Considering the declining supply of energy sources and the increase in their usage, photovoltaic thermal (PVT) technology is eliciting gaining considerable interest. A PVT collector is a combination of a PV panel and a thermal collector in a single unit to simultaneously generate electricity and thermal energy. The main components of a PVT collector are PV panel, absorber, working fluid, and insulator. PVT solar collectors convert solar radiation directly into electrical and thermal energies. A PVT air collector consists of a PV panel and a thermal collector system. The system can produce electrical energy directly converted from sunlight, extract heat from the PV panel and warm the air flow inside the collector [1]-[13].

Tonui and Tripanagnostopoulos [14] developed a simple analytical model using the Fortran90 programming language, based on the energy balance equations between the PVT components, airflow and the ambient and validated against experimental data. This model used the program which uses iterative process to fix the initially guessed unknown parameters accurately and to converge after a few iterations.

This model proved to indicate the difference between the predicted values and experimental data for air outlet temperature to be less than 1°C. Tonui and Tripanagnostopoulos [15] proved that the air outlet temperature reduces with increasing channel depth. It was found that the fin system results in production of higher outlet temperature than the thin metal sheet and conventional air collector system for any channel depth. This is due to the increased heat extraction by the fins and the thin metal sheet system gives slightly higher outlet temperature than the conventional air collector system due to increased heat exchange surface. Furthermore, they also verified that the thermal and electrical efficiency reduce with increasing channel depth. The thermal efficiency reduced due to the reduced flow rate while the electrical efficiency decreased due to the increase in PV temperature as the depth increased. It was also found that the fin system performed better, for both thermal and electrical, than the other two systems. The thin metal sheet system gave better thermal energy but marginally better electrical efficiency than conventional air collector system.

The objective of this review is to describe types of PVT air collectors. In addition, to present some of the published research papers of PVT air collectors during the year 2010-2019. In this review, also presented heat transfer and energy modelling of dual channel PVT air collectors.

## 2. STUDIES CONDUCTED ON PVT AIR COLLECTORS IN 2010-2019

Overview of studies on PVT solar air collectors are reviewed. Various types of PVT air collectors have been designed and evaluated experimentally and theoretically. These collectors are generally classified according to the air flow pattern, that is, below the absorber, whether air flows above the absorber, on both sides of the absorber, in single and in double pass. The performances of PVT air collectors can be evaluated through economic and environmental impact analyses. Enviro-economic and exergo-economic analyses of PVT air collectors were also studied. In addition, researchers have also studied environmental-economic-exergy-energy-analyses of PVT air collectors. Some of the published studies conducted on PVT air collectors during the year 2010-2019 are reported in Table 1 [16-55].

Table 1. Summary of study available on PVT air collectors in 2010-2019 [16-55]

Year	Contents of Study	Author(s) and Reference
2010	Energy-economic analysis of theoretical and experimental study	Agrawal and Tiwari [16, 17]
2010	Energy analysis of theoretical and experimental study	Sarhaddi et al. [18]
2010	Energy-exergy analysis of theoretical and experimental study	Sarhaddi et al. [19]
2010	Energy analysis of theoretical and experimental study	Shahsavar and Ameri [20]
2011	Energy-exergy analysis of theoretical study	Agrawal and Tiwari [21]
2012	Energy analysis of theoretical study	Amori and Al-Najjar [22]
2012	Energy-exergy analysis of theoretical and experimental study	Agrawal et al. [23]
2013	Energy-exergy-environmental analysis of experimental study	Agrawal and Tiwari [24]
2013	Energy-exergy-environmental analysis of experimental study	Rojaria et al. [25]
2014	Energy analysis of theoretical and experimental study	Yang and Athienitis [26]
2014	Energy analysis of experimental study	Kim et al. [27]
2014	Energy analysis of experimental study	Amori and Al Raheem [28]
2015	Energy analysis of theoretical and experimental study	Li et al. [29]
2015	Energy analysis of experimental study	Good et al. [30]
2015	Energy analysis of experimental study	Ahn et al. [31]
2015	Energy-exergy-economic analysis of theoretical study	Jahromi et al. [32]
2015	Energy analysis of theoretical study	Kamel and Fung [33]
2015	Energy-exergy-enviro-economic analysis of theoretical study	Rajoria et al. [34]
2016	Energy-exergy analysis of experimental study	Gholampour and Ameri [35]
2016	Energy analysis of theoretical study	Rounis et al. [36]
2016	Energy analysis of theoretical and experimental study	Mojumder et al. [37]
2016	Energy-exergy analysis of theoretical and experimental study	Hazami et al. [38]
2016	Energy-exergo-economic analysis of experimental study	Tiwari and Tiwari [39]
2016	Energy analysis of theoretical and experimental study	Slimani et al. [40]
2016	Energy analysis of theoretical and experimental study	Tabet, et al. [41]
2017	Energy and exergy analysis of theoretical study	Ooshaksaraci et al. [42, 43]
2017	Energy analysis of theoretical study	Zohri et al. [44]
2017	Energy analysis of experimental study	Zohri et al. [45]
2018	Energy and exergy analysis of theoretical study	Zohri et al. [46]
2018	Exergy analysis of theoretical study	Zohri et al. [47]
2018	Energy and exergy analysis of experimental study	Das et al. [48]
2018	Energy and exergy analysis of theoretical and experimental study	Fudholi et al. [49]
2018	Energy-economic analysis of theoretical study	Nazri et al. [50]
2018	Energy analysis of theoretical study	Nazri et al. [51]
2018	Energy analysis of experimental study	Nazri et al. [52]
2018	Energy analysis of theoretical and experimental study	Nazri et al. [53]
2019	Energy and exergy analysis of theoretical study	Abdullah et al. [54]
2019	Exergy analysis of theoretical and experimental study	Fudholi et al. [55]

Recently, Fudholi et al. [55] studied theoretical and experimental on energy and exergy analysis of PVT air collector with different mass flow rate and intensity. Fudholi et al. [56], [57] reviewed energy and exergy analysis for PVT air collectors. In 2018, PVT air collectors were reviewed in detail [58], [59].

### 3. TYPES OF PVT AIR COLLECTORS

PVT is the popular system of a solar energy system. PVT air collector is designed to receive solar energy and convert it into electrical and hot air (thermal); in this device, thermal is transferred into air that flows into the collector. A PVT air collector consists of a PV panel, an insulation and a frame as well as one or more glass cover (Figure 1A) or a transparent material placed over the absorbing plate with air flowing around it. The efficiency of PVT air collectors can be enhanced by using extended heat transfer area through the absorber with finned absorbers (Figure 1B), corrugated surfaces (Figure 1C), porous media (Figure 1D) and honeycomb absorber (Figure 1I). PVT air collectors can be categorised into four types are: (i) conventional PVT air collector, which single-pass with a channel below a PV panel or known as back-pass PVT air collector (Figure 1A), (ii) PVT air collector with extended heat transfer area (Figure 1A, B, C, I), (iii) with thermal storage (Figure 1E, J), and (iv) hybrid PVT air collector (Figure 1F, G, H). Figure 1F shows the combination of thermoelectric modules with PVT air collector. Figure 1G and Figure 1H shows the combination air-water/nanofluids-based PVT collector.

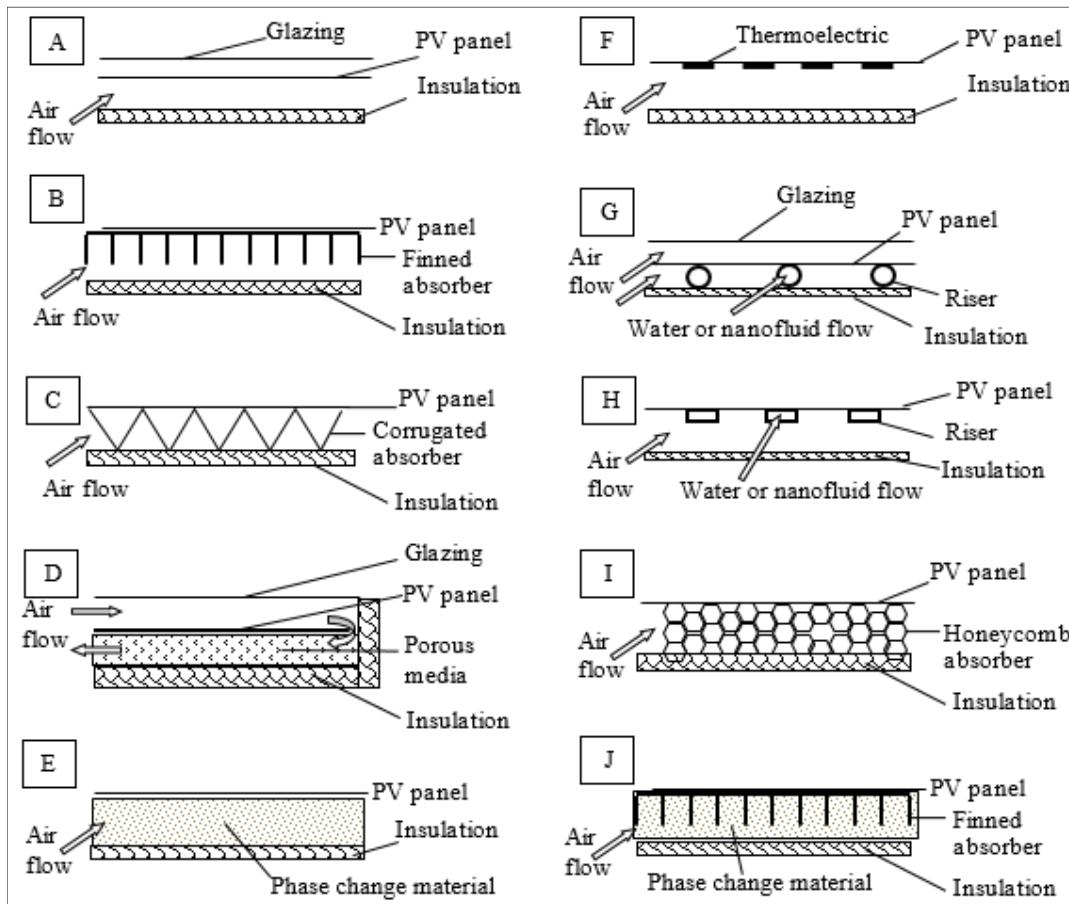


Figure 1. Various types of flat-plate PVT air collectors

### 4. STUDIES CONDUCTED ON DUAL CHANNEL PVT AIR COLLECTORS

Several studies conducted on the energy and exergy analyses of dual channel PVT air collectors as shown in Table 2. Hegazy [60] comprehensively investigated the overall performances of PVT air collectors. This investigation was based on single glazing collectors, where air flows over the absorber (Model I) or

below it (Model II) and on both sides of the absorber in a single pass (Model III) or in a double pass (Model IV). The results concluded that for a given collector design, the temperature of the PV decreases due to an increase in flow rate, thereby improving the electrical efficiency of the collector. Among the four PVT models, Model 1 displayed the lowest overall performance, whereas Model III exhibited the highest overall performance, followed by Model IV. For Model III (known as single-pass dual channel PVT air collector, as shown in Figure 2), they reported that PV, thermal and PVT efficiencies of 6.9%-8.1%, 30%-56% and 34.3%-61.4%, respectively. Shahsavar et al. [61] studied energy and exergy analyses of a dual channel PVT air collector with and without glass cover. For the glazed system, it is found that PV, thermal, and PVT energy efficiencies of 8.1%-9.1%, 31.6-36.2%, and 39.8%-44.9%, respectively, during the day where as PV, thermal, PVT Exergy efficiencies of 3.9%-6.7%, 0.9%-1.1%, and 4.8%-7.7%, respectively. For the unglazed system, it is evident that there are variations of PV, thermal, and PVT energy efficiencies of 9.6%-10.6%, 12.2%-24.8%, and 22.5%-34.6%, respectively, during the day where as PV, thermal and PVT Exergy efficiencies of 5.7%-8.7%, 0.3%-0.5%, and 6%-9%, respectively. Shan et al. [62] also investigated several of PVT air collectors. They established energy balance equations and mathematical models of PVT air collectors with glass cover for five cases. They reported that for single-pass dual channel PVT air collector (Case 4), PV and thermal efficiencies of 4.7%-5.7% and 59%-61%, respectively. Amori and Abd-AlRaheem [63] studied various PVT air collectors. They reported that for single-pass dual channel PVT air collector, PV and thermal efficiencies of 5%-12% and 58%-77%, respectively. Sing et al [64] proposed dual channel semitransparent photovoltaic thermal (DCSPVT). They presented that PV efficiency and PVT Exergy efficiency of ~12%-16% and 22%-58%, respectively. Ooshaksaraei et al. [65] developed four new designs of PVT air collectors with bifacial solar cells. In Model IV, the air flows between the glazing and the PV lamination and returns back to the second channel. For Model IV, they reported that energy and exergy efficiencies range from 51% to 67% and from 3.9% to 9.5%, respectively.

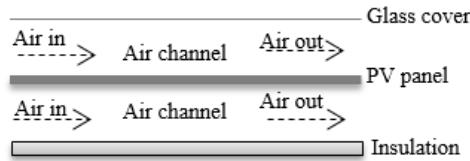


Figure 2. Schematic of single-pass dual channel PVT air collector

Table 2. Studies conducted on energy and exergy analysis of dual channel PVT air collectors

Reference & year	Study	Energy efficiency (%)			PVT exergy efficiency
		PV	Thermal	PVT	
[60], 2000	Theoretical	6.9-8.1	30-56	34.3-61.4	-
[61], 2012	Theoretical and experimental	8.1-10.6	12.2-36.2	22.5-44.9	4.8-9
[62], 2014	Theoretical	4.7-5.7	59-61	-	-
[63], 2014	Theoretical and experimental	5-12	58-77	-	-
[64], 2016	Theoretical and experimental	12-16	-	-	22-58
[65], 2017	Theoretical and experimental	-	-	51-67	3.9-9.5

## 5. MATHEMATICAL MODEL OF DUAL CHANNEL PVT AIR COLLECTORS

Shahsavar et al. [61] analysed the energy and exergy performances of a naturally ventilated PVT air collector in Kerman, Iran. A thin metal sheet was used as a collector to improve the heat extraction of the PV panel and increase the thermal and electrical outputs. The energy balance of this PVT air collector, as shown in Figure 3, is expressed as follows.

For the glass cover:

$$\alpha_g I A dx = (h_{r,pvg} + h_c)(T_g - T_{pv}) A dx + (h_{r,gs} + h_w)(T_g - T_a) A dx \quad (1)$$

For the PV panel:

$$\begin{aligned} \tau_g \alpha_{pv} (1 - \eta_{pv}) I A dx &= h_{pva} (T_{pv} - T_a) A dx + h_{pvf1} (T_{pv} - T_{f1}) A dx \\ &+ h_{r,pvp} (T_{pv} - T_p) A dx \end{aligned} \quad (2)$$

For the upper air channel:

$$\dot{m}_{f1} C_p dT_{f1} = h_{pvf1} (T_{pv} - T_{f1}) A dx + h_{pf1} (h_p - T_{f1}) A dx \quad (3)$$

For the thin metal sheet:

$$h_{r,pvp} (T_{pv} - T_p) A dx = h_{pf1} (T_p - T_{f1}) A dx + h_{pf2} (T_p - T_{f2}) A dx + h_{r,pb} (T_p - T_b) A dx \quad (4)$$

For the lower air channel:

$$\dot{m}_{f2} C_p dT_{f2} = h_{pf2} (T_p - T_{f2}) A dx + h_{bf2} (h_b - T_{f2}) A dx \quad (5)$$

For the back insulation:

$$h_{r,pb} (T_p - T_b) A dx = U_b (T_b - T_a) A dx + h_{bf2} (T_b - T_{f2}) A dx \quad (6)$$

For the unglazed type:

$$\alpha_{pv} (1 - \eta_{pv}) I A dx = h_w (T_{pv} - T_a) A dx + h_{pvf1} (T_{pv} - T_{f1}) A dx + h_{r,pvp} (T_{pv} - T_p) A dx \quad (7)$$

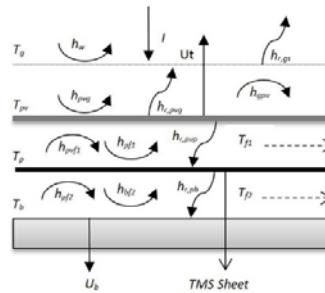


Figure 3. Schematic of a PVT air collector with temperatures and heat transfer coefficients

Singh et al. [64] analysed the thermal modelling and performance of a two-channel, semi-transparent PVT system. The overall efficiency performance of the two-inlet, semi-transparent PVT was higher than the one-pass semi-transparent PVT system. The energy balance of this PVT air collector, as shown in Figure 4, is expressed as follows.

For the top glass channel:

$$U_{pvf1} (T_{pv} - T_{f1}) b dx = \dot{m}_{f1} C_{f1} \frac{dT_{f1}}{dx} + U_t (T_{pv} - T_a) b dx, \quad (8)$$

Where

$$h_{pvf1} = \left[ \frac{L_g}{k_g} + \frac{1}{h_{f1}} \right]^{-1} \text{ And } U_t = \left[ \frac{L_g}{k_g} + \frac{1}{h_{pva}} \right]^{-1}. \quad (9)$$

For the PV panel:

$$\alpha_c \tau_g^2 I \beta_c b dx = h_{pvf1} (T_{pv} - T_{f1}) b dx + h_{pvf2} (T_{pv} - T_{f2}) b dx + \eta_{pv} \alpha_g^2 F I b dx, \quad (10)$$

Where

$$U_{pvf1} = \left[ \frac{L_g}{k_g} + \frac{1}{h_{f1}} \right]^{-1}. \quad (11)$$

For the down air channel:

$$U_{p\bar{v}f2}(T_{p\bar{v}} - T_{f2})b dx + h_{p\bar{f}2}(T_p - T_{f2})b dx = \dot{m}_{f2}C_{f2}\frac{dT_{f2}}{dx} + U_{f2a}(T_{f2} - T_a)b dx, \quad (12)$$

Where

$$U_{f2a} = \left[ \frac{L_p}{k_p} + \frac{L_I}{k_I} + \frac{1}{h_I} \right]^{-1}. \quad (13)$$

For the blackened absorbing plate:

$$\alpha_p \tau_g^3 I(1-F) bdx = h_{pf2}(T_p - T_{f2}) bdx + U_b(T_p - T_a) bdx, \quad (14)$$

Where

$$U_b = \left[ \begin{smallmatrix} L_I \\ k_I \end{smallmatrix} + \frac{1}{h_I} \right]^{-1}. \quad (15)$$

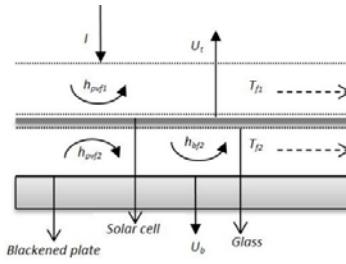


Figure 4. Schematic of the two-inlet, semi-transparent PVT system with temperatures and heat transfer coefficients

Ooshaksaraei et al. [65] analysed the energy and exergy of dual channel PVT air collectors as shown in Figure 5(a). Figure 5(b) shows the various heat transfer coefficients of the dual channel PVT air collector considered. An energy balance model was developed to analyse the performance. The energy balance equations for dual channel PVT air collector can be expressed as follows.

For the glass cover:

$$S\alpha_G + h_{rlg}(T_L - T_g) = h_{cga}(T_g - T_a) + h_{cgf1}(T_g - T_{f1}) + h_{rgs}(T_g - T_s) \quad (16)$$

For the PV laminate:

$$S\tau_g\alpha_{PV}P(1-\eta_{PV_{front}}) + S\tau_g\tau_L(1-P)\eta_R\alpha_{PV}(1-\eta_{PV_{rear}}) = h_{cLf1}(T_L - T_{f1}) + h_{rLg}(T_L - T_g) + h_{cLf2}(T_L - T_{f2}) + h_{rLR}(T_L - T_R) \quad (17)$$

For the reflector:

$$h_{RL}(T_L - T_R) + S(1 - P)\tau_L(1 - \eta_R)\tau_g = h_{cRf2}(T_R - T_{f2}) + U_R(T_R - T_a) \quad (18)$$

For fluid 1:

$$h_{cgf1}(T_g - T_{f1}) + h_{clf1}(T_L - T_{f1}) = \frac{mc_{f1}}{b} \frac{dT_{f1i}}{dx_{f1i}} \quad (19)$$

For fluid 2:

$$h_{cL_{f2}}(T_L - T_{f2}) + h_{cR_{f2}}(T_R - T_{f2}) = \frac{mc_{f2}}{b} \frac{dT_{f2i}}{dx_{f2i}} \quad (20)$$

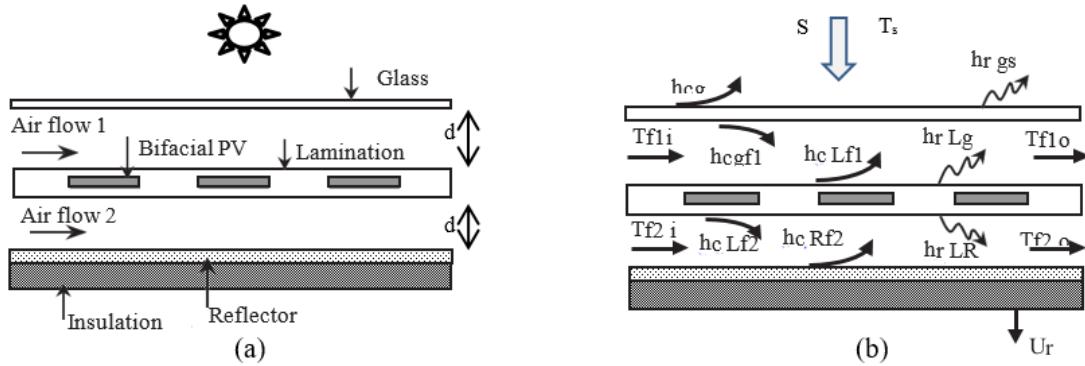


Figure 5. (a) Schematic of a dual channel PVT air collector, (b) with temperatures and heat transfer coefficients

## 6. CONCLUSIONS

PVT air collector is used to remove heat accumulated in a PV panel and reuses the waste heat in an appropriate way. PVT air collector combines the PV panel and solar collector into a single module, thereby enabling PV-cell cooling and simultaneously utilising the extracted heat for domestic use. Heat transfer and thermal modelling of dual channel PVT air collectors are presented. Generally, steady-state one-dimensional linear first-order differential equations were reported for solution of mathematical model. Energy and exergy efficiencies of dual channel PVT air collectors were 22.5%–67% and 3.9%–58%, respectively.

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